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LOW-COST SOLAR ARRAY PROJECT

PRODUCTION PROCESS AND EQUIPMENT TASK

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A MODULE EXPERIMENTAL PROCESS SYSTEM DEVELOPMENT UNIT (MEPSDU)

QUARTERLY REPORT NO. 4

September 1, 1981 to November 30, 1981

CONTRACT NO. 955909

The JPL Low-Cost Silicon Array Project is sponsored by the U. S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, by agreement between NASA and DOE.

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I. CONTRACT GOALS AND OBJECTIVES

The objective of this contract is to determine technical feasibility of the production of photovoltaic modules designed to meet all specifications described in JPL Document 5101-138 and fabricated using single crystal silicon dendritic web sheet material. This determination of technical feasibility will be accomplished by:

A. The selection, design, and implementation of a solar cell processing and photovoltaic module assembly sequence in a Module Experimental Process System Development Unit (MEPSDU),

B. Performance of technical feasibility experiments in which a sufficient number of modules will be produced in the MEPSDU facility to allow assessment of production costs,

C. Passing of acceptance and qualification tests by modules produced during the demonstration runs, and

D. Determination of a 1986 module FOB mass production cost in a fully automated, 25 MW/yr capacity facility using the MEPSDU process sequence as calcualted by SAMIS using cost data generated during completion of the demonstration runs (Item B, above).

II. SUMMARY

Work on the Westinghouse MEPSDU contract was initiated on November 26, 1980. This report describes work performed during the fourth three-month period of the contract (September 1, 1981 through November 30, 1981) and outlines plans for the next quarter.

Module design work during the past quarter resulted in the identification of surface treatment to the module glass superstrate which improves module efficiencies by approximately .5% (absolute). This improvement has been verified by testing conducted at Westinghouse. This is an important breakthrough which could reduce production costs by as much as 2.5¢/watt.

The final module environmental test, a simulated hailstone impact test, was conducted on full size module superstrates at Westinghouse during this quarter. The objective of the test was to verify that the module's tempered glass superstrate can withstand specified hailstone impacts near the corners and edges of the module. No breakage occurred, and glass panels have been assembled and shipped to JPL for further testing with high velocity iceball impacts.

Process sequence design work continued throughout the quarter on the metallization process selection, liquid dopant investigation, dry processing, and antireflective/photoresist application technique tasks. An optimum Ti/Pd thickness has been established. Work on the identification of commercial grade dopants which could allow simultaneous front and back junction diffusions has led to promising results. An experiment has been performed to identify a noncontact cleaning method for raw web cleaning. In addition, a vendor has agreed to apply antireflective and photoresist coatings to dendritic web strips using a meniscus coating technique to allow a qualification of this improved process.

Work on the Kulicke and Soffa task to design an automated cell interconnect station for the Westinghouse MEPSDU continued this quarter. Emphasis was placed on the design of a cell string conveyor, the design of an interconnect feed system, the design of rolling ultrasonic spot bonding head, and the identification of the optimal commercially available programmable control system.

SAMIS economic analyses were updated during this quarter and have reaffirmed that the Westinghouse MEPSDU process sequence can meet the DOE/JPL cost goals of $.70 per peak watt (in 1980$).

III. TECHNICAL PROGRESS

A. MEPSDU Module

1. Module Design

The assembly drawing of the prototype Westinghouse MEPSDU module was included in MEPSDU Quarterly Report No. 2 (Westinghouse TME 3110, Figure 1). This is the module which will be fabricated for the MEPSDU program in the Westinghouse pre-pilot facility and delivered to JPL prior to installation of the MEPSDU facility. Cells for the prototype module will be fabricated using the MEPSDU baseline process sequence; however, minor module dimensional changes may be possible in the final MEPSDU module to take advantage of improved fabrication equipment being procured in the MEPSDU program.

Figure 1 is a photograph of one of the first prototype MEPSDU modules fabricated in the Westinghouse pre-pilot facilities. Module efficiency levels up to 10.6% have been demonstrated to date. This efficiency is the ratio of the measured module output power to the product of the insolation level and the glass surface area. Efficiency levels of 12% will be achieved using the baseline process sequence in conjunction with improved control techniques.

The MEPSDU module assembly drawing specifies a superstrate of 1/8 inch thick tempered glass with an iron content of less than 0.03%. With this low iron content, the solar transmittance in the 0.4 to 1.2 μm wavelength range is 91%. This is a significant improvement over standard tempered glass which transmits less than 87%. The loss in transmittance is mainly (≈80-90%) a reflection loss.

Working with a vendor during the past quarter, an even greater transmittance was achieved through a proprietary surface treatment. This treatment is based on work initiated on an ERDA program(1) and improved by later industry studies(2). The treatment consists of etching the glass in a controlled manner to produce micro-pores on the surface (10-30Å across) which act as an antireflective

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(1) Phase II Final Report, COO-2930-12 to ERDA from Honeywell Corporation.

(2) Zuel Corporation, St. Paul, Minnesota.

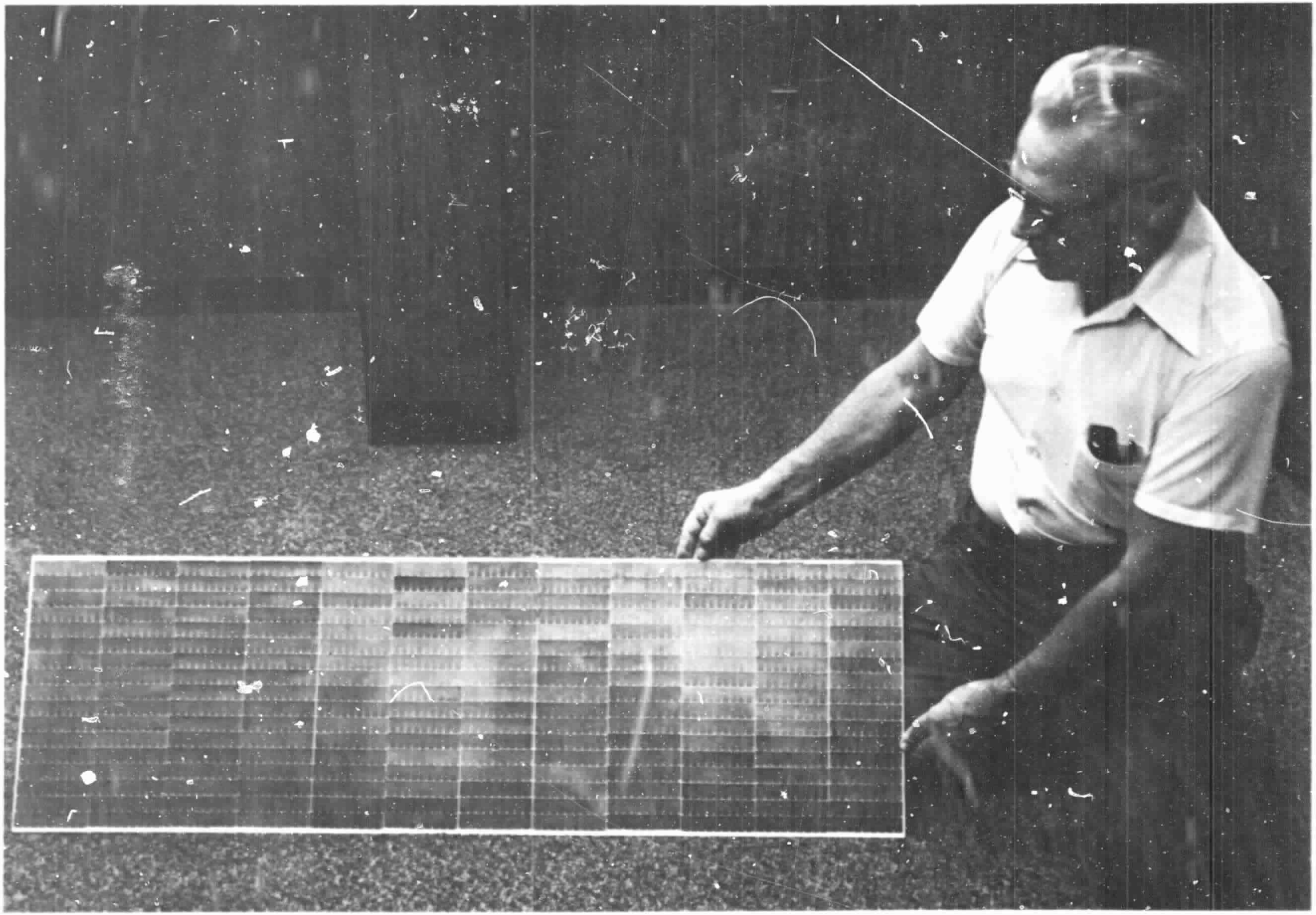

Figure 1. Prototype MEPSDU Module Fabricated in Westinghouse Pre-Pilot Facility

coating. The index of refraction of this surface matches the glass-air interface and reduces reflection losses.

Several pieces of module sized glass (nominal 16" x 48") have been subjected to this surface treatment. The treated surfaces show a bluish tint as would be noted with a very thin antireflective coating. Tests indicate that this treated glass increases the transmittance from 91% to 95%. On a high efficiency module (≈12%), this increased transmittance translates into about 0.5% absolute increase in module efficiency.

Several laminations have been carried out using this glass without difficulty.

Samples of this glass have been on test at the Los Alamos Test Center for over 12 months, and no degradation in transmittance has been noted.

If this glass is to be specified for the MEPSDU module, life tests as well as strength tests must be carried out to assure that the treatment does not reduce the residual stress in the tempered glass. In addition, a cost-benefit analysis must be made to determine if the cost decrease due to the increased efficiency offsets the increased cost due to the glass surface treatment.

2. Environmental Testing

Simulated hailstone impact tests were performed during the past quarter using a 1.0 inch diameter pellet composed of tungsten powder in an ice matrix. For these tests, the drop height was selected to be 79.2 inches, so that the tungsten-ice sphere would deliver the same energy (1.53 ft-lbs) to the glass surface as the design basis hailstone. The spheres were freshly made, frozen with liquid nitrogen then conditioned at -10°C overnight; longer conditioning, i.e., a few days, allows the ice to sublime from the surface of the sphere, leaving behind a layer of unbonded powder. To minimize the possibility of abrasion of the sphere in the chilled release tube, the tube bore was 1.020 inch diameter. The impact point selected was the corner of the glass plate.

The results of the tests were positive in that the glass did not shatter. Instead the sphere shattered, and fragments were scattered around the point of impact. The point of impact, however, was not precisely the point of aim. The center of the tungsten smudge on the glass closest to the corner was on the long edge 3/8 inch away from the corner, an error possibly caused by the greater clearance in the release tube.

Three full-size simulated modules were laminated and bonded to test frames using the adhesive configuration specified by the Westinghouse MEPSDU module interface drawing. These test articles were delivered to JPL for high velocity iceball impact tests as specified by JPL Document 5101-138. The glass superstrate of one of the test articles is the treated glass discussed above. Preliminary testing conducted at Westinghouse indicates that the 1/8" thick tempered glass module superstrate can survive the hailstone impact tests.

3. Laminate Environmental Tests

Environmental testing of twelve small "mini" modules continued during the past quarter. These modules, which were described in the previous quarterly progress report (Westinghouse TME 3110), were made to evaluate several different layups, substitutes for Korad-KLEAR as the back surface weather seal, and Tedlar tape as an edge seal. Cells with efficiency levels unacceptably low for incorporation into modules were selcted for use in these tests. Cut window glass was used on all the test modules rather than tempered float glass which will be used on the MEPSDU modules.

Figure 2 shows the measurement of the performance characteristics before and after the series of events occurring from lamination through the completion of 200 thermal cycles for mini-module G-2. This module, with the exception of an added layer of Craneglas over the cells that was found to be unnecessary, is representative of the MEPSDU module layup. The data shown in Figure 2 is typical of the data obtained on the other mini-modules in that the modules have exhibited no performance or visual sensitivity to sustained environment testing.

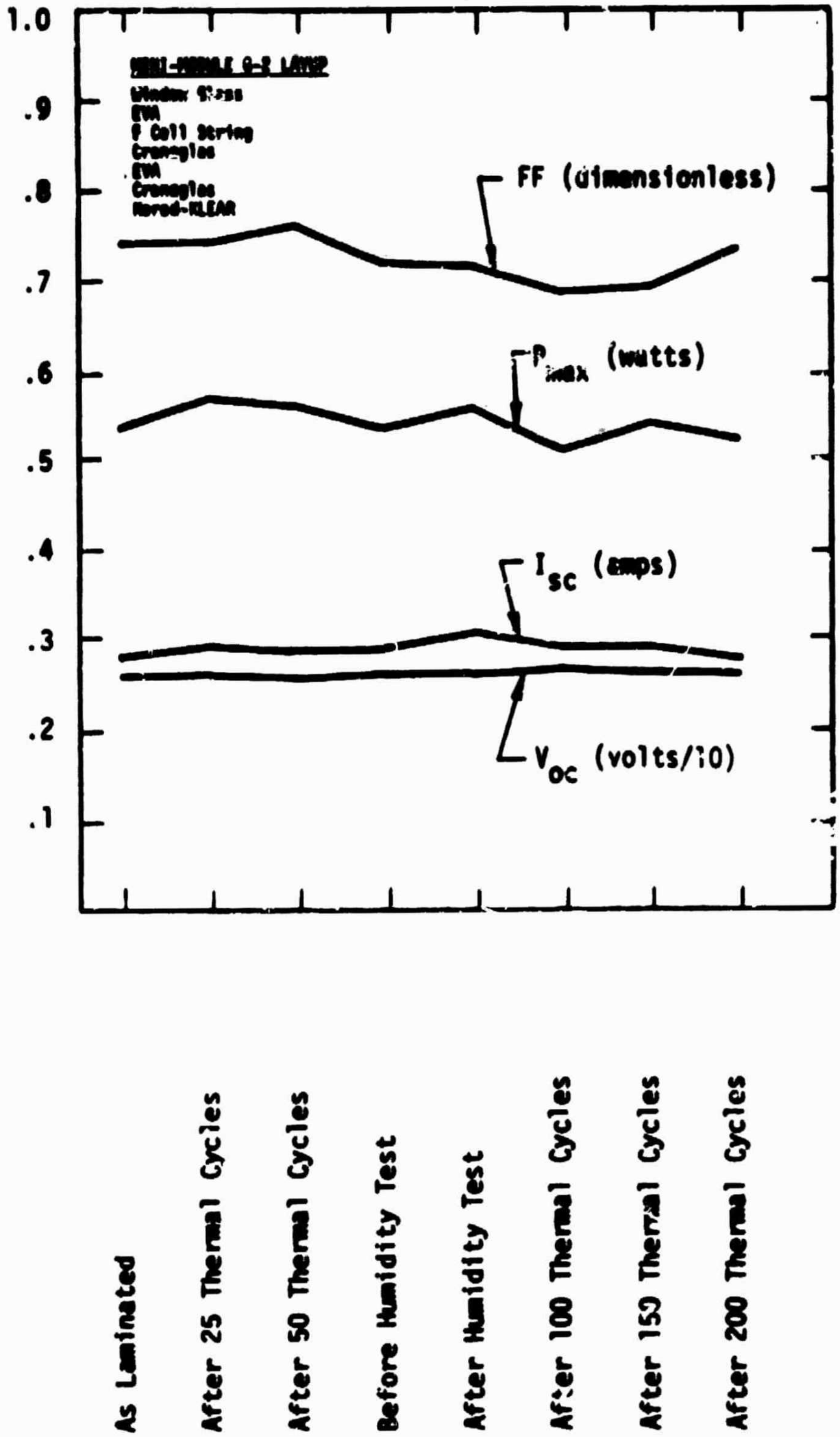

Figure 2. Environmental Test Data from Mini-Module G-2

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B. Process Sequence Design

The preliminary "baseline" process sequence for the Westinghouse MEPSDU has remained essentially unchanged from that which was presented at the preliminary design review held in March and outlined in the initial quarterly progress report (Westinghouse TME 3090). During the past quarter, investigations were continued into four selected areas of the sequence in an attempt to demonstrate the potential for reducing processing costs below the level evaluated for the baseline sequence. Areas being investigated include: alternate, more cost-effective metallization procedures; ion implantation of front and back junctions to replace the diffusion and its associated masking/cleaning steps; liquid precursor films for diffusion masks and dopants; and dry processing (plasma etching) to reduce wet chemical usage. Each of these areas will be discussed in further detail.

1. Metallization Process Selection

The initial baseline Westinghouse MEPSDU process sequence specified a metallization system comprised of evaporated layers of Ti, Pd, and Ag followed by an electroplated layer of Cu. During the past quarter, an in-house effort was directed toward the study of alternate metallization schemes which could improve the cost effectiveness of the baseline metallization system by reducing costs of the metals used or identifying less expensive equipment for applying the metals.

Numerous experiments were conducted in which electroless nickel was deposited on the surface of the silicon web. In all cases, the inability to deposit a continuous, adherent nickel film on the web in a minimum number of process steps has made this approach less attractive than the reliable evaporation process identified in the baseline sequence. These results, in conjunction with results of a separate DOE/JPL sponsored program (Contract No. 955909) conducted recently at the Westinghouse R&D center which suggest that nickel is not an effective long-term diffusion barrier for copper, have led to abandoning the use of electroless nickel on the Westinghouse MEPSDU.

Concurrent with the effort to develop electroless nickel, experiments have been conducted to improve the baseline evaporative diffusion barrier configuration. These tests have confirmed that copper will plate as well or better on Pd as on Ag. Hence, the baseline process sequence has been modified and improved through the elimination of the Ag evaporation step.

Several tests were conducted to establish a total evaporated metal thickness and an optimum Ti:Pd ratio. Presently, a metallized layer of 1000Å Ti/300Å Pd appears to be satisfactory. The increased total thickness does not hinder excess metal rejection, and the extension of the Ti layer above the AR coating minimizes the risk of entrapping copper in an area where it could be detrimental should undercutting of the AR occur during etching.

Adherent copper plating has been obtained on palladium that was not plasma ashed after the rejection of photoresist and excess metal. This is contrary to experience in plating copper on silver. Because of the benefits derived from eliminating a process step, the effects of this change upon cell characteristics were monitored in subsequent tests.

Two runs were made recently in which cells made from dendritic web silicon processed with and without the ashing step could be compared. Although the copper to palladium adherence was excellent in all cases, there was an indication that cells processed without ashing had, with some exceptions, efficiencies that were about 1 to 3% lower than the efficiencies of cells processed from web that had the intermediate ashing step. This could be due to the presence of residual photoresist on the AR coating. Because of the potential benefits of eliminating a step from the process sequence, investigations of the effects of processing without ashing will continue.

2. Liquid Precursor Films for Diffusion Masks and Dopants

The objective of this task is to identify modifications to the baseline diffusion process sequence which can reduce costs by using less expensive chemicals, less involved procedures, simplified equipment and controls, and improve the automatability of the process.

Gaseous diffusion of boron and phosphorous to form the solar cell back and front junctions respectively is specified for the MEPSDU baseline process sequence. Since these diffusions must be done at significantly different temperatures (960°C for boron, 850°C for phosphorous), the diffusion processes require separate furnaces, significant web handling, etc. Although gaseous diffusion produces high efficiency cells and has been shown to meet the JPL/DOE cost goals, an alternative technique using doped liquid precursors as diffusion sources is under study.

Initial experiments were conducted using several commercial grade dopants having different concentrations. Web coated with these dopants was processed at different temperatures to determine if suitable sheet resistivities for the n+ and p+ surfaces could be obtained. The main emphasis in the initial phase of the study was placed on finding materials and concentrations which would yield the proper sheet resistivities* when diffused at the same temperature for the same time period. This would allow simultaneous diffusion of the p-type and n-type dopant source in a single furnace. Based on results of these experiments, more extensive tests were made using a commercial liquid dopant which in the early experiment showed promise.

The tests were carried out as follows:

1. Boron dopant applied to one side of web strip and baked.
2. Phosphorous dopant applied to opposite side of web strip and baked.
3. Strip heated in an 80% N_2 - 20% O_2 ambient and then slow cooled to 700°C.
4. Basel process sequence used to finish processing strip into cells.

The first group of cells processed in this experiment had sheet resistivities which fell out of the given specification, with the p+ resistivity being 70-150 Ω/□ while the n+ resistivity was 25-35 Ω/□ .

*The MEPSDU specifications for sheet resistivity are:

Boron doped p+: 40 ±10 Ω/□
Phosphorous doped n+: 60 ±10 Ω/□

The efficiency of the cells processed from these diffusion experiments was 10.4 ±0.6% with a maximum efficiency of 11.3%. The efficiency was generally inversely proportional to the p+ sheet resistivity.

Several subsequent tests were made using liquid dopants from different suppliers and having different dopant concentrations. Table 1 gives the results from several of these tests. The table shows that cells fabricated from the same web growth run using liquid dopants have consistently lower efficiencies as compared to those fabricated using the gaseous diffusion process of the base-line MEPSDU process sequence. This lower efficiency is due in part to non-optimum n and p sheet resistivities (p+ sheet resistivity is high by 25-50% while n+ is low by 25%).

Another factor which became more obvious during these tests is the poor surface quality of many of the cells after diffusion. This surface problem leads to irregular coverage of the AR coating and poor Cu plating. This surface effect is believed due to the technique used for applying the liquid dopant. In tests conducted to date, the dopant has been applied using a sponge-squeegee method. After diffusion and diffusion glass removal, streaky surface color irregularities are noted which are apparently related to the dopant application. These same irregularities are then noted after the AR coating and electroplating step.

Due to the potential cost advantage of this process, this work will continue with emphasis on other methods of dopant application such as spinning and meniscus coating.

In addition to the effort on liquid dopants, experimental work on the use of liquid precursor films for diffusion masks continued this quarter. In the baseline Westinghouse MEPSDU process sequence, a chemically vapor deposited SiO_2 (Silox) film is used as a diffusion mask to protect the non-diffused side of the web in each of the two diffusion steps. Experiments are now under-way where a liquid precursor (an organic silicon compound in an organic solution) replaces the "Silox." The first experiments, using the antireflective

TABLE 1

COMPARISON OF CELLS PRODUCED USING THE BASELINE PROCESS (GASEOUS DIFFUSION) AND LIQUID DOPANTS

Web Growth Run		Web Quality (Efficiency - %)		
No.	Ⓦ Designation	Baseline Process η_o	Liquid Dopant η_1	η_1/η_o
1	6·100	---	12.1	---
2	4·81	12.6	8.2	.65
3	1·120	12.9	10.6	.82
4	4·82	13.8	7.1	.51
5	7·47	11.3	10.6	.94
6	5·102	13.9	10.9	.78

NOTES: 1. All cells - 2.0 cm x 9.8 cm.
2. Tested at AM-1; 100 mW/cm^2.

coating, were unsuccessful due to poor coverage of the surface and contamination of the silicon from the decomposition products of the antireflection coating. In later experiments, other liquid precursors were applied using paint-on application techniques. The results were again unsuccessful due to nonuniform coverage of the liquid. Further experiments are currently underway in which the liquid precursor will be applied using a meniscus coating application technique.

Figure 3 is a schematic drawing of the meniscus fluid coater. The fluid is applied to a porous applicator. The substrate (web) is drawn across the top of the fluid meniscus which forms at the top of the applicator. The thickness of the meniscus (dimension t in Figure 3) is greater than the radius of web dendrites, and the fluid is applied evenly on the surface of the web. The application experiments are being performed by the meniscus coating equipment vendor. It is hoped that this application technique can be used for liquid dopants, antireflective coatings, and photoresist coatings as well as diffusion masks.

3. Dry Processing

The objective of this task is to investigate the use of dry plasma processing to replace the wet chemistry steps identified in the baseline process sequence. These include pre-diffusion cleaning, oxide removal, and surface clean-up prior to metallization and plating.

From results of in-house experiments and based on discussions with vendors of plasma systems, it has been determined that the most effective use of dry plasma processing in the Westinghouse MEPSDU sequence would be in the initial raw web/pre-diffusion cleaning step of the process. The use of plasma etching to remove the post-diffusion boron or phosphorous containing glasses would be intolerably slow, and its use in the pattern defining oxide etch step would not be desirable because of unfavorable oxide/silicon etch ratios with standard etching gases.

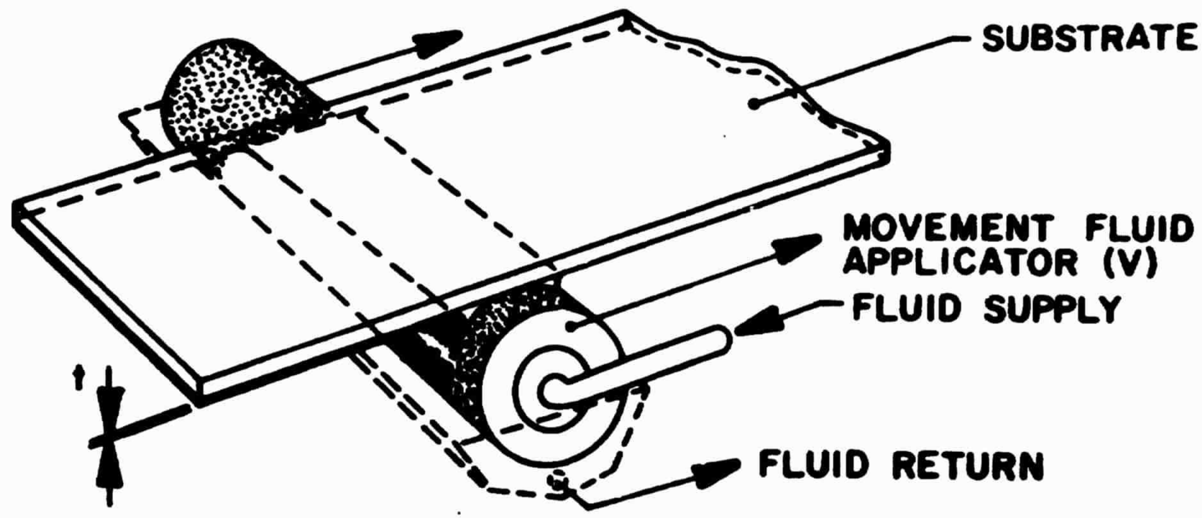

Figure 3. Meniscus Coating of Precursor Fluids to Dendritic Web Silicon

The principal benefit in using plasma etching in the initial raw web/pre-diffusion cleaning sequence is that it replaces three of four wet chemical cleaning operations and minimizes handling not only of the web, but also of the chemical solutions that require make-up, maintenance, and disposal. An HF soak and scrub to remove growth oxide from the web prior to plasma etching would be the one remaining wet chemical operation.

Work on this task during the past quarter was focused on developing a non-contact cleaning method to replace web scrubbing operations. Samples were sent out for vendor trials of cleaning in a "Megasonic" unit to determine if it will effectively remove oxide particles from the web surface in preparation for plasma etching. In these trials, a Megasonic cleaner modified for use with HF was filled with a solution of 1 part of HF in 10 parts of water and agitated. Samples of dendritic web with growth oxide on their surfaces were placed in the solution (equilibrium temperature of 45°C) for times up to 9 minutes. Samples processed in this manner were not completely free of loose oxide; however, there was an improvement with time. Thus, longer immersion times, stronger solutions, or other solutions may be effective. Arrangements are being made to follow-up on this process.

In addition to this Megasonic cleaning trial, the evaluation of several batches of plasma etched web processed in the Westinghouse pre-pilot line is in progress.

C. MEPSDU Design

This task is associated with the design or specification of equipment required to perform all operations of the Westinghouse MEPSDU process sequence. Final selection of most items has been deferred due to FY'81 budget reductions. However, the status of all equipment is summarized below.

1. Pre-Diffusion Cleaning Equipment

As described in the previous section of this report, substantial investigative work is currently underway to replace wet chemical cleaning operations of the baseline process sequence with dry processing operations. Because of this

effort, preparation of equipment specifications for this operation have not yet been initiated.

If Megasonic cleaning test results are positive, equipment specifications (E-Specs) for Megasonic raw web cleaning and plasma pre-diffusion cleaning devices with the required throughput capacity will be prepared during the next quarter.

2. Diffusion Furnace

An equipment specification was prepared for the diffusion furnace system required to perform front and back junction formations, as included in the baseline process sequence. Firm fixed price quotations were received from four vendors. A final selection has been postponed until early 1982. Due to the planned delay, it will be necessary to obtain new quotations on the equipment regardless of specification development.

In addition, a preliminary E-Spec for the CVD Silox reactor, required to deposit the SiO_2 diffusion barrier on the web strips to prevent simultaneous front and back side diffusion, has been prepared. However, as discussed earlier in this report, it is hoped that this equipment will be replaced by a liquid meniscus coating apparatus.

3. AR and PR Application Stations

A proposal has been received from a vendor to design and fabricate an AR/PR application station. The proposed equipment would automate the dip/slow withdrawal/bake operations of the baseline process sequence for both AR and PR applications.

During the past quarter, numerous experiments were conducted to identify an alternate technique for applying AR and PR coatings to dendritic web silicon. The baseline dip and withdrawal application has the primary disadvantage that the coatings must be applied to both sides of the web whereas the coatings are required only on the front (sun) side.

Spray, spin-on, brush, and meniscus application techniques have all been investigated. Of these processes, only meniscus coatings have the uniformity required. The application technique and equipment are identical to that described in Section B2 of this report.

Small samples of web with AR and PR coatings that were vendor applied using a meniscus coating system were returned for evaluation early in this quarter. The Westinghouse AR coating solution was applied by the vendor at an initial speed of 12 inches per minute. With continued experimentation the speed dropped in one day's time to 2.5 inches per minute because of thickening of the solution due to the combined effects of solvent evaporation and moisture pick-up from a high humidity environment. The coating thickness was determined as applied by a subjective judgment of color. Samples baked at 400°C and returned for evaluation were a uniform dark blue. Measurements made using an "Alpha-Step" indicated an AR coating thickness of 700-800Å which is in the desirable range. The Shipley 1350-J photoresist applied by the vendor gave a coating that measured one micron thick. This coating was well within photolithographic tolerances. When masked, exposed, and developed, the PR produced a satisfactory cell pattern; and these results are very strong indications that meniscus coating of AR and PR materials can be substituted for the dip coat processes of the baseline process sequence.

Full-size dendritic web silicon strips and a sample of the Westinghouse anti-relfective coating solution have been sent to the vendor of meniscus coating equipment for processing. After AR coating is applied, the strips will be returned for processing into qualification cells along with material going through the pre-pilot line.

A conceptual equipment design, a description of the station component functions, and a budgetary cost estimate were also received from the vendor. The cost of the meniscus coating system was lower than those of the automated AR/PR coat and bake station. In addition to a cost advantage, the meniscus coating system appears to have the following other advantages over the dip and bake station:

- Ease of loading and unloading to and from a vacuum pallet (no labor intensive fixturing/no clamps to cause web breakage).
- Horizontal conveyoring of rows of single layers of web than can flow directly into the exposure station.
- One side only coating for better utilization of coating solutions and extended life of developing and etching baths.
- Operable with small solution volumes and includes viscosity adjustment/solvent make-up controls.

Additional follow-up and the preparation of an equipment specification for this station are planned for the next quarter.

4. Expose/Develop/Etch Station

During the past quarter, work was initiated on the study of exposure control, developing, and pattern etching. The object of this study was to establish developing and etching parameters amenable to automatic machine handling concepts by the elimination of operator visual operations used for control on the Westinghouse pre-pilot facility.

Discussions, held with a leading supplier of photoresist, led to recommendations on photoresist thickness, exposure, and development. The vendor is supplying a sample of a modified version of the developer that is now in use and will be more economical in that it can be used at a greater dilution with no loss in development quality or speed. Types of development equipment suitable for MEPSDU production throughput were also discussed with this vendor.

Work has been initiated with another vendor on the design and fabrication of a high throughput exposure station. Conceptually, this equipment will hold a number of strips of web (40 cm long) in a vacuum chuck. A lid, holding the plastic masks, will be lowered onto the web. With the lid closed and held in place with vacuum, the masks will be in direct contact with the web strips. An exposure lamp will be mounted on a track above the fixture and will move along the length of the fixture exposing the photoresist through the mask.

The preliminary design is scaled to give sufficient output for the MEPSDU line.

5. Metallization Station

An E-Spec has been prepared for the metallization station required to perform base metal application (Ti/Pd) specified in the baseline process sequence. Firm fixed price quotations have been received from five vendors. A final selection has been postponed until early 1982 due to program funding reductions. Since the current quotes will expire prior to final selection, updated quotations will be solicited from each of the vendors.

6. Metal Rejection/Plating Station

A preliminary equipment specification has been initiated for the copper electroplating system, but its completion has been deferred until work on the overall metallization process sequence selection has been completed. This will occur in early 1982.

7. Cell Separation Station

In the MEPSDU process sequence, the separation of the discrete solar cells from the dendrite-web matrix is accomplished by scribing the cell outline on the back of the web strip and fracturing out the individual cells. This scribing is accomplished using a Nd:YAG laser to penetrate into the back surface of the web strip about one third of its thickness.

An equipment specification for a laser scribe suitable for the MEPSDU throughput has been prepared. Quotations were received from three vendors, and a formal vendor selection was made during this quarter. A contract for this station has been placed with Quantronix Corporation.

The laser scribe system described in the equipment specification consists of the following elements:

1. Nd-YAG laser powered by krypton arc lamps.

2. Positioning fixture such that the web can be aligned to assure proper scribing directions and distances. This alignment is specified to be automatic - the operation constrained only to placing the web strip in a defined area. (This item is of prime importance in meeting the MEPSDU throughput requirement.)

3. A control unit which can be programmed to drive the fixture (or move the laser beam) through the required scribing path.

Since placing the laser scribe order, a coordination and status review meeting was held at Quantronix in which web hold-down techniques, location of cell alignment marks, and banking surface considerations were discussed; and all currently identified problems were resolved.

A preliminary design review meeting has been scheduled for December 16 at Westinghouse in which Quantronix personnel will present a system description and submit panel and chassis outline and arrangement drawings.

8. Cell/Module Test Stations

Both the solar cell and module test stations have been placed on order. Equipment is being designed and fabricated by Spectrolab, Incorporated. The order consists of a M.A.P.S.S. solar simulator (medium area light source) and a semi-automatic cell test system to be interfaced with the M.A.P.S.S. data system. Since the MEPSDU line will require testing a cell every five seonds and a module every half hour, it has been rationalized that a single data acquisition system can be utilized to interface with both a small area and large area light source and their associated data channels.

A coordination meeting was held at the vendor's (Spectrolab) facility during the past quarter. At the time of the meeting (November 10), all M.A.P.S.S. hardware was currently in-house including the Data General computer. Assembly work was approximately 70% complete and on schedule for the December 18, 1981, shipment. The cell test portion of the equipment will be delivered in the first quarter of 1982. The vendor is currently developing a quotation for an automated cell loader and sorter which could be used in conjunction with the cell tester.

A prototype MEPSDU module and four reference solar cells, all fabricated on the Westinghouse pilot facility during the past quarter, will be shipped to Spectrolab in early December for qualification tests on the M.A.P.S.S.

D. Kulicke and Soffa Subcontract

1. General

Westinghouse has selected Kulicke and Soffa (K&S) Industries, Inc., as its subcontractor for the design and development of MEPSDU equipment dealing with the automation of interconnection and assembly of its dendritic web silicon solar cells into modules. This subcontract deals with design, development, testing, and operation of equipment, and preparation of instruction manuals for the automated interconnect station.

The solar cell electrical interconnect configuration to be utilized by the interconnect station will be thin (.0015") aluminum tabs connecting metallized pads located on the front surfaces of each cell with the metallized rear surface of the adjacent cell. A major innovation in the Westinghouse cell interconnect station is the ultrasonic bonding technology to be used to join aluminum tabs to metallized cell surfaces. A rolling spot bonding technique has been developed by K&S specifically for this application.

The Westinghouse module will incorporate 12 separate cell string assemblies. Each cell string assembly will contain 15 individual cells electrically connected in series. The 12-cell string assemblies will be positioned by the automated cell interconnect station equipment to form an array of 12 rows of 15 cells each, with nominal dimensions of 16 x 48 inches. The target machine cycle is 5 seconds/cell with a yield of 95% or better. The machine will also include substations for making subsequent parallel or bus bar electrical interconnections of the 12 individual cell string assemblies.

During this quarter, work on the K&S subcontract focused on design of the cell string conveyor, modification of the bond head for use with the conveyor, and design of the interconnect feed system. Work continued on other machine

stations and layouts of the tabbing section (first half) of the machine. Figure 4 is a schematic of the automated cell interconnect station showing the individual mechanical subsystems which are described below.

2. String Conveyor

A steel belt conveyor and a shuttle system were evaluated to determine the mechanism best suited for use as the cell string conveyor. The belt conveyor uses two parallel steel belts driven by sprocketed pulleys. The belts index continuously. Cells are transferred to the conveyor onto precise "pockets" defined by registration/retaining hardware on the belts. The pockets maintain the accuracy of intercell pitch (distance between cells).

The shuttle uses a reciprocating table, or plate, driven by a lead screw. The length of the plate corresponds to the length of the cell string to be made. The plate begins in a reset position at the cell transfer area and indexes (advances) one intercell pitch as each cell is deposited on the plate. After the complete string is formed, the plate indexes to the string pickup area, where the string is transferred to the module array area. The shuttle then returns to its reset position. The return to reset is an additional motion not required by the belt conveyor. However, the shuttle recovers this lost time by requiring less time for each index cycle. Cells can also be transferred to the shuttle faster because it uses no pockets, eliminating the additional care and time required to transfer a cell to such precise locations. The shuttle's reliability depends on the accuracy of cell transfer and elimination of any movement of the plate in relation to the cells during index cycles.

Based on the following factors, the shuttle was chosen as the system to be used for the string conveyor:

1. Handling and transfer of the cell to the shuttle presents fewer problems, minimizing the chance for cell breakage.
2. The shuttle's design allows optimizing intercell pitch to accommodate manufacturing tolerances. Index pitch is a programmable function and may be changed with minimal changing of parts.
3. The shuttle is a relatively simple mechanism, containing few parts, and should be less expensive.

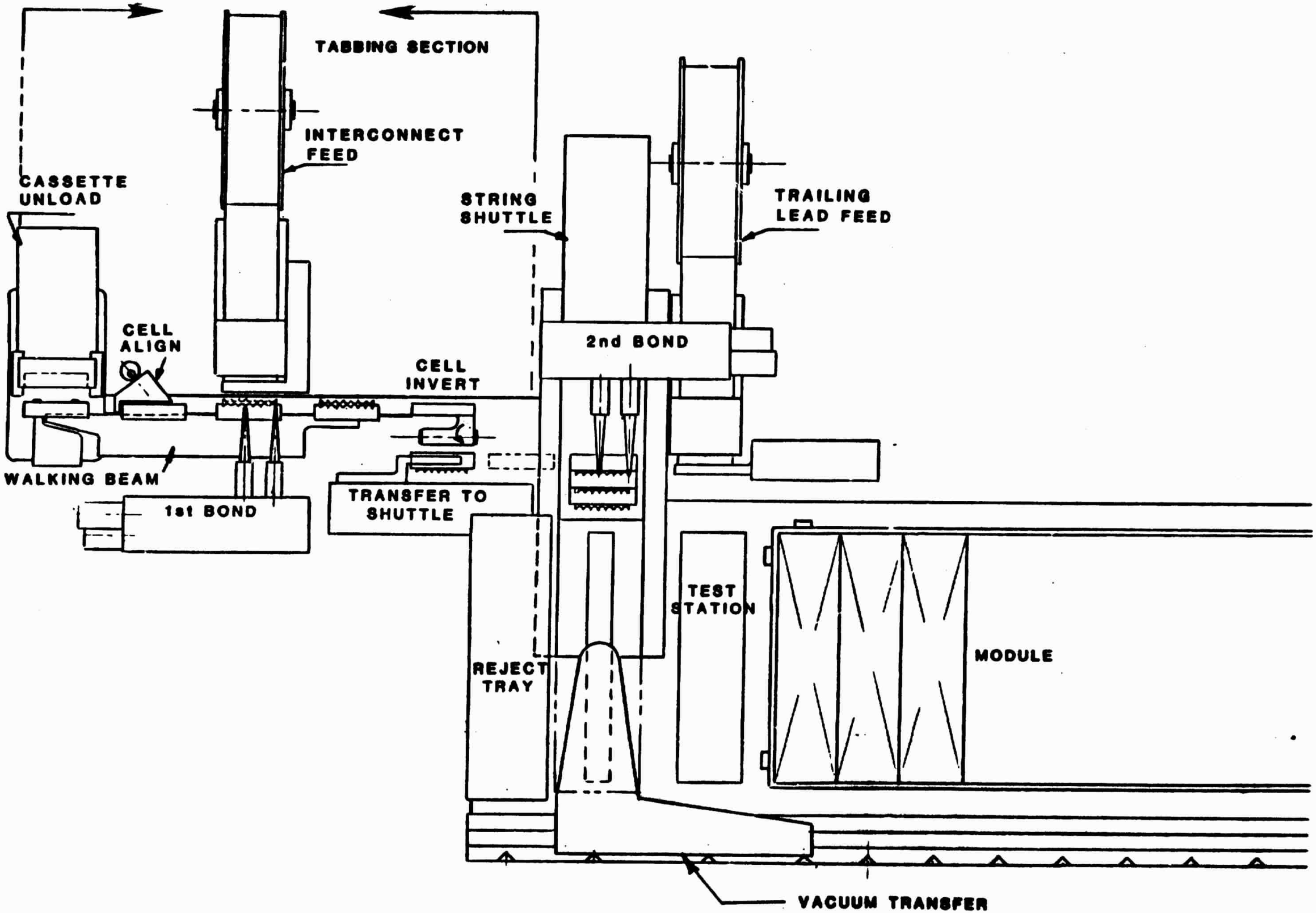

Figure 4. Westinghouse MEPSDU Automated Cell Interconnect Station

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Work on design details of the shuttle is proceeding. Use of the shuttle required some modification of bond head design. This modification is described below.

3. Bond Head

In the bond head design used with the belt conveyor, the tool horn was mounted to a tapered roller bearing. The centerline of tool horn rotation was aligned with the top (bonding) surface of the belts, but the lower portion of the bearing was below the belt surface. To accommodate use of the shuttle, this "underhang" was eliminated, since it would interfere with the shuttle plate. The tool horn now rotates on a half bearing located above the centerline. This design gives the bond head the ability to extend over a table, which facilitates bonding of the trailing leads. Also, these bond heads can be used on both first and second bond station of the machine, making the design universal and parts interchangeable. Design details for the bond head have been completed, and a prototype bond station (bond heads and interconnect feed) is under construction.

4. Interconnect Feed System

The design for the interconnect feed system has been completed. Quotes for interconnect foil have been received from vendors and procurement has been initiated. The possibility of using individual ribbons was investigated in the interest of material savings. However, studies indicated that the presently proposed interconnect configuration is more desirable from the standpoint of machine/process problems and cost effectiveness. A prototype bond station, including interconnect feed and bond head, is currently under construction.

5. Cell Alignment Station

The design for the cell alignment station has been completed. Parts will be procured pending completion of detailed drawings.

6. Walking Beam

The design for the walking beam has been completed. Detailed drawings are being developed in preparation for procurement of parts.

7. Control System

With the advent of more advanced commercial programmable controllers (PC's), the original selection was reevaluated to determine the unit best suited for the machine. This further evaluation resulted in the selection of a GE Model 600 unit which has the high technical specifications required for this application. The unit's high scan speed (1 msec/1 K), eliminates the additional software and associated hardware development that would be required to adapt previously available controllers. The PC works in conjunction with a programming terminal capable of providing ladder diagrams, simulation data and diagnostic data on the terminal's CRT screen for development and troubleshooting purposes, which makes the unit more desirable from a user standpoint.

Work is proceeding on determining the complete machine sequence of events and developing timing diagrams to aid the programming effort. A block diagram of the control structure for first and second bond stations, including the PC and some microprocessor controls, is shown in Figure 5.

8. Design Review

A design review of the automated cell interconnect station was conducted at the K&S facility at Horsham, Pennsylvania, in November. The Westinghouse design review team consisted of the MEPSDU Program Manager and two senior engineering personnel (one electrical and one mechanical) who are not directly related to the MEPSDU project. The primary purpose of the review was to establish that the equipment proposed by K&S could meet the requirements of the automated cell interconnect station equipment specification (E-Spec). This evaluation is necessary prior to placing the order for the Westinghouse funded equipment.

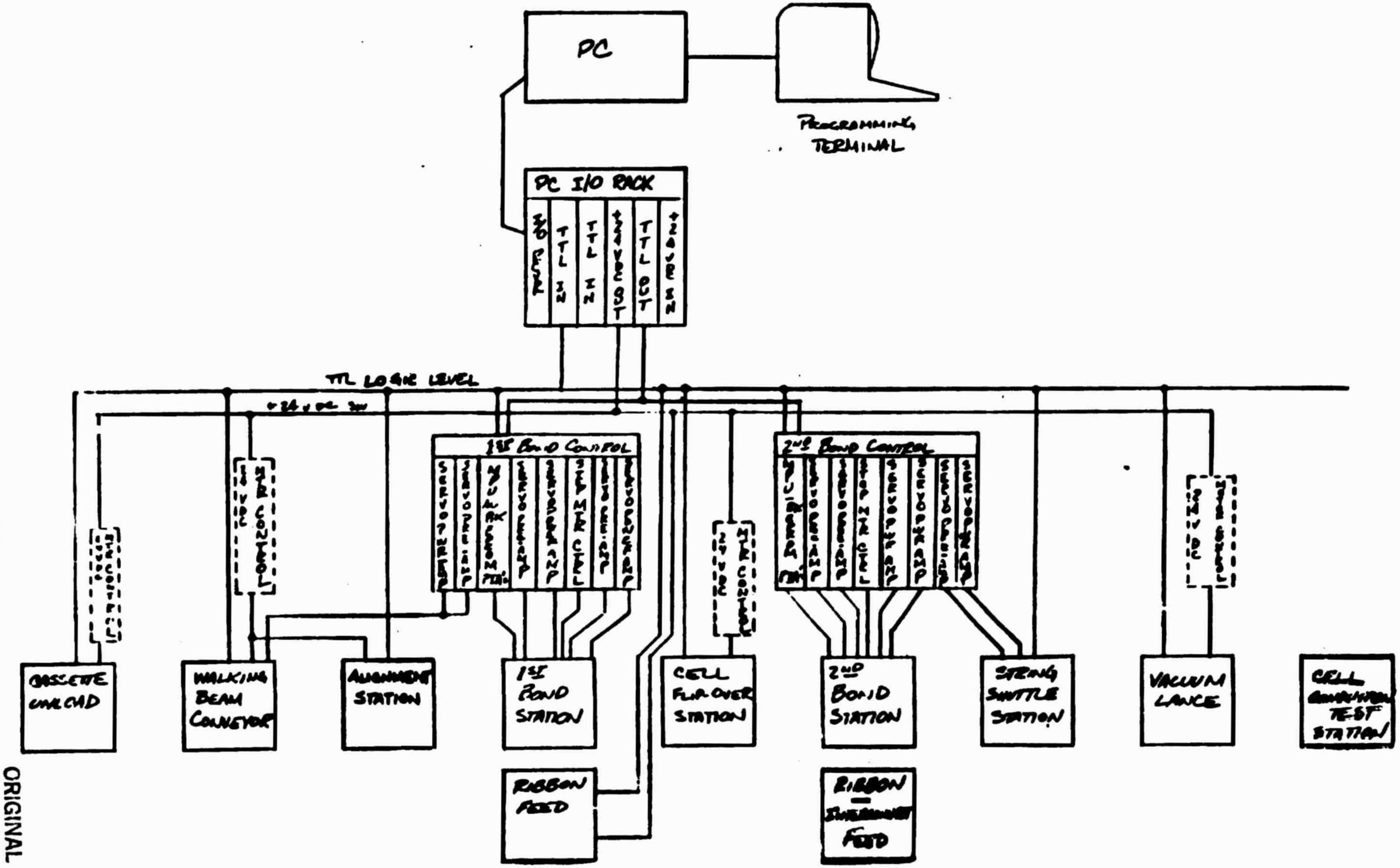

Figure 5 Interconnect Station Control Structure

The evaluation team report has been completed and indicates that K&S proposed equipment should meet the E-Spec requirements both electrically and mechanically. Accordingly, the capital equipment order should be placed with K&S in early 1982.

E. Preliminary Cost Analysis

The baseline process sequence for fabricating solar modules from dendritic web silicon in the Westinghouse MEPSDU has been analyzed using SAMICS methodology. This economical analysis is being conducted in iterative fashion in parallel with technical work on the contract. Results of the first economic analysis iteration were sumbitted to JPL in July and were summarized in the previous quarterly report (Westinghouse TME 3132).

A workshop was held with JPL personnel during the past quarter to discuss the inputs and results of the preliminary cost analysis (SAMICS) submitted by Westinghouse for 1MW/yr or 25MW/yr production facilities.

The following modifications were agreed upon based at the meeting:

- In the initial cost analysis, a process yield was taken at only two points in the process sequence. These were two dummy stations (one after cell test and one after module test) which were inserted into the process sequence for calculational purposes. It was decided a more accurate approach would be to assume a realistic yield at each process step so as to prevent the assumption of additional processing on a rejected element.

- A revised estimate is needed for the labor requirements on the 1MY/yr line. The present analysis assumed that one person would be used at each processing station, even if not fully occupied.

- The maintenance and quality control personnel should be costed to the specific process steps where they are required rather than costed uniformly over all process steps.

- Machine up-time (A8 on Format A) should be adjusted for each station to best industry experience.

- The usage of several commodities should be recalculated based on new information.

- Vendor estimate backup should be supplied for the commodity and capital equipment costs.

Subsequent to the meeting, the Format A's were modified in accordance with the suggestions. A second simulation was then carried by Westinghouse, and a set of revised Format A's were supplied to JPL for their evaluation.

The updated analysis was carried out for the 1 MW/yr facility (MEPSDU) as well as a 25 MW/yr production facility. The latter simulation is to assure that the MEPSDU process sequence is an efficient step toward high volume-low cost production. In the following discussion and tables, the 1 MW/yr facility is referred to as the M-process while the 25 MW/yr facility is referred to as the P-process.

In the Format A's and simulations for the M and P processes, the individual steps within the process sequence are the same. This makes it simple to compare individual process steps and cost drivers, as well as comparisons between the two processes.

The Format A's for the M and P simulations have been based on:

- New or reverified vendor quotes for capital equipment and commodities,
- Recalculated commodity usage,
- Vendor input for utility usage,
- Experience gained on the 50 kW pre-pilot facility.

The basic assumptions are as given in previous quarterly reports except that the yield factors for the latest simulation are taken into account at each process step rather than at two specific steps (cell testing and module testing).

Table 2 gives the results of the value added per process step for the M-process simulation, while Table 3 gives the same data for the P-process. Table 4 gives a breakdown for the two process sequences which indicates the cost drivers in the process.

From these simulations, it has been concluded that scaling up the 1 MW/yr MEPSDU sequence to a 25 MW/yr production facility will lead to a cost effective manufacturing sequence that essentially meets the DOE/JPL cost goals of $0.70 1980 $/watt in 1986.

F. Documentation

All programmatic documentation specified in the Westinghouse MEPSDU contract has been submitted in accordance with schedular requirements. A list of the programmatic documentation and submittal dates are compiled in Table 5.

G. Activities Planned for Next Quarterly Reporting Period

The fifth quarter of the Westinghouse MEPSDU Program covers the period from December 1, 1981, through February 28, 1982. At the direction of JPL, a revised program plan for the contract is currently being developed. The revision will reduce contract expenditure rates and is required by JPL to comply with DOE budgetary restrictions. As a result of this replanning, activities for the next quarterly reporting period have not yet been finalized. However, engineering efforts will be focused on the preparation and finalization of equipment specifications for long-lead MEPSDU stations.

Work on the Kulicke and Soffa automated cell interconnect station subcontract in the fifth quarter of the project will continue on individual machine stations, particularly the cell transfer device, the shuttle, and the bond station. For

TABLE 2

SAMICS COST ANALYSIS

Value Added for Process Steps

1 MW/yr Production Facility

Process Step	Process	Value Added (1980$/peak watt)	% Total
1	Prepare Input Web	0.615	18.9
2	Boron Diffusion	0.192	5.9
3	Phosphorous Diffusion	0.181	5.6
4	Application of AR/PR	0.182	5.6
5	Define Grid Pattern	0.193	5.9
6	Metallize Web	0.357	10.9
7	Rejection and Plating	0.307	9.4
8	Cell Separation and Test	0.576	17.7
9	Cell Interconnection	0.254	7.8
10	Lamination	0.345	10.6
11	Crating	0.061	1.9

Total for Process - 3.27 $\frac{1980\$}{\text{Peak Watt}}$

TABLE 3

SAMICS COST ANALYSIS

Value Added for Process Step

25 MW/yr Production Facility

Process Step	Process	Value Added (1980$/peak watt)	% Total
1	Prepare Input Web	0.340	49.5
2	Boron Diffusion	0.033	4.5
3	Phosphorous Diffusion	0.024	3.3
4	Application of AR/PR	0.016	2.2
5	Define Grid Pattern	0.017	2.4
6	Metallize Web	0.037	5.1
7	Rejection and Plating	0.046	6.3
8	Cell Separation and Test	0.029	4.0
9	Cell Interconnection	0.026	3.6
10	Lamination	0.121	16.6
11	Crating	0.019	2.5

Total for Process - 0.709 $\frac{1980\$}{\text{Peak Watt}}$

TABLE 4

SAMICS COST ANALYSIS

Value Added per Watt Cost Factors for
the 1 MW/yr and 25 MW/yr Simulations

(All Costs in 1980$)

	1 MW/yr	25 MW/yr
Direct Labor	0.820	0.060
Direct Materials	0.539	0.388
Direct Utilities	0.033	0.008
Indirect Labor	0.469	0.038
Indirect Materials	0.060	0.004
Indirect Utilities	0.044	0.005
Capital Expenses	0.770	0.111
Taxes/Misc.	0.521	0.095

TABLE 5

PROGRAMMATIC DOCUMENTATION SUBMITTAL STATUS

	ITEM	SUBMITTAL DATE(S)
1.	COST ESTIMATES	
	a. Baseline	December 17, 1980
	b. Revised	May 22, 1981
2.	SCHEDULE ACCOMPLISHMENT REPORT/FINANCIAL REPORT	December 17, 1980 January 14, 1981 February 16, 1981 March 16, 1981 April 16, 1981 May 16, 1981 June 16, 1981 July 16, 1981 August 17, 1981 October 15, 1981 November 16, 1981
3.	PROGRAM PLAN AND WBS	
	a. Original	December 17, 1980
	b. Revised	May 22, 1981
4.	MONTHLY TECHNICAL PROGRESS REPORT	January 15, 1981 February 15, 1981 March 15, 1981 April 15, 1981 May 15, 1981 June 4, 1981 July 6, 1981 August 6, 1981 September 8, 1981 December 11, 1981
5.	PRELIMINARY DESIGN REVIEW PACKAGE	February 19, 1981
6.	MODULE DESIGN REVIEW PACKAGE	June 30, 1981
7.	QUARTERLY TECHNICAL PROGRESS REPORT	March 15, 1981 June 15, 1981 September 15, 1981

completed designs, such as the bond head, interconnect feed, cell alignment station, and walking beam, parts will be released for manufacture. Preliminary assembly will begin upon receipt of parts. In addition, control programming effort will begin for completed stations. To aid this effort, work will proceed on determining the complete sequence of events and developing timing diagrams.